The Dual Higgs Mechanism and the Origin of Mass in the Universe *

A.Aurilia †
Department of Physics
California State Polytechnic University
Pomona, CA 91768

E. Spallucci ‡
Dipartimento di Fisica Teorica, Università di Trieste, Italy
and
Istituto Nazionale di Fisica Nucleare, Sezione di Trieste, Italy

Abstract

The idea that a background of invisible material pervades the whole universe is as old as the history of natural philosophy. Modern particle physics and cosmology support that idea and identify in the cosmic vacuum the ultimate source of matter-energy, both seen and unseen, in the universe. In the framework of the inflation-axion scenario, we suggest an unusual realization of the Higgs mechanism which converts the latent energy of the vacuum into observable mass. The existence of a new spontaneously broken symmetry is pointed out which has the same effect of the Peccei-Quinn symmetry in creating axions as pseudo-Goldstone bosons. However such particles are eliminated from the physical spectrum in favor of massive pseudoscalar particles.

* *Honorable Mention* Awarded Essay by the Gravity Research Foundation
† e-mail address: aaurilia@csupomona.edu
‡ e-mail Address: spallucci@trieste.infn.it

The fundamental paradigms of modern physics are the standard Big Bang model of cosmology and the standard $SU(3)_{\mathrm{C}} \otimes SU(2)_{\mathrm{L}} \otimes U(1)_{\mathrm{Y}}$ model of the strong and electroweak interactions. During the past decade both models have been refined with the addition of two key ingredients: *inflation* on the cosmological side and *axions* as pseudo Goldstone bosons associated with the spontaneous breakdown of the Peccei-Quinn symmetry in particle physics.

Inflation requires the existence of dark matter and axions have long been candidates for cold dark matter, even though there is no a priori reason why the two notions should be related at all.

If the cosmological constant today is zero, and there are claims to the contrary [1], the axion could be detected in an experiment capable of probing masses in the range $10^{-6} \sim 10^{-3}$ eV. Where does this mass come from? The general consensus is that it comes from the quantum anomaly which violates the chiral $U(1)_{\mathrm{PQ}}$ symmetry, thereby evading Goldstone's theorem.

However, the chiral anomaly is just one of at least two possible loopholes by which the existence of a Goldstone boson can be avoided . The second loophole is the Higgs mechanism. Our objective is to suggest a variation of the Higgs mechanism which appears to be tailor made for the axion-mass problem but operates entirely within the framework of the inflationary cosmology. We call this novel mechanism the " dual " (abelian) Higgs mechanism, or DHM for short, since it applies to a totally antisymmetric tensor gauge field $A_{\mu\nu\rho}$ which is the dual of the vector gauge field encountered in the usual Higgs model.

In order to place DHM in the right perspective and partly to motivate it, consider the inflationary idea that the early phase of the exponential expansion of the universe inflated a microscopic volume of space to a size much larger that the presently observable part of the universe; this idea can be formulated within the framework of general relativity as a special case of " Classical Bubble Dynamics " (CBD), i.e. the study of the evolution of a vacuum bubble in the presence of gravity [2–4]. In our own formulation of CBD [4], inflation is driven by a temporary field $A_{\mu\nu\rho}$ which is equivalent to a cosmological constant and DHM is the precise mechanism that converts the self-energy of $A_{\mu\nu\rho}$ into observable mass. How does this conversion take place? The following properties of $A_{\mu\nu\rho}$ constitute the crux of DHM in the inflation-axion scenario:

a) First, $A_{\mu\nu\rho}$ represents " dark stuff " by definition, since in (3+1)-dimensions $A_{\mu\nu\rho}$ does not possess radiative degrees of freedom. In fact, the field strength $F_{\mu\nu\rho\sigma} \equiv \nabla_{[\,\mu} A_{\nu\rho\sigma\,]} = \partial_{[\,\mu} A_{\nu\rho\sigma\,]}$ is simply a constant disguised as a gauge field. This property, even though peculiar, is not new in quantum field theory: it is shared by all n-forms in n-spacetime dimensions. For instance in two dimensions, $F_{\mu\nu} = \partial_{[\,\mu} A_{\nu]} = \epsilon_{\mu\nu} f$ while in four dimensions, $F_{\mu\nu\rho\sigma} = \epsilon_{\mu\nu\rho\sigma} f$, and f represents a constant background field in both cases by virtue of the field equations. What is then the meaning of " f "? As a gauge

field, $A_{\mu\nu\rho}$ is endowed with an energy momentum tensor and thus it couples to gravity: the resulting equations are Einstein's equations with the cosmological term $\Lambda = 4\pi\, G\, f^2$. For this reason we call $A_{\mu\nu\rho}$ the "*cosmological field*".

b) Second, if the cosmological field acquires a mass, then it describes massive *pseudoscalar* particles, in sharp contrast with the usual Higgs mechanism. For instance, in Minkowski space the field equations

$$\partial^\mu\, F_{\mu\nu\rho\sigma} - m^2\, A_{\nu\rho\sigma} = 0 \tag{1}$$

are equivalent to the set of equations

$$\left(\, \partial^2 - m^2\, \right)\, A_{\mu\nu\rho} = 0\ ; \qquad \partial^\mu\, A_{\mu\nu\rho} = 0 \tag{2}$$

and the supplementary condition imposes three constraints on the four components of $A_{\mu\nu\rho}$ leaving only one propagating degree of freedom: $\partial^\mu A^*_\mu$ where A^*_μ is the (pseudo)vector dual to $A_{\mu\nu\rho}$.

c) Third, $A_{\mu\nu\rho}$ does not interact directly with ordinary matter fields. Rather, it is the " gauge partner " of relativistic closed membranes, or bubbles, in the sense that it mediates the interaction between surface elements according to the same general principle of local gauge invariance which dictates the coupling of point charges to vector gauge bosons. What is then the gauge structure of bubble dynamics? It has long been known [5] that relativistic extended objects possess a new kind of $U(1)$ gauge symmetry involving multilocal phase transformations of the wave functional which represents the extended object. Thus, if $\Phi[\,\Sigma\,]$ is the (complex) functional of the membrane configuration $\Sigma : X^\mu(\,\xi^1, \xi^2\,)$ modelling the bubble in terms of local coordinates $(\,\xi^1, \xi^2\,)$, then the action functional must be invariant under the combined transformation

$$\delta_\Lambda\, A_{\mu\nu\rho} = \partial_{[\,\mu}\, \Lambda_{\nu\rho\,]} \qquad (\Lambda_{\nu\rho} = -\Lambda_{\rho\sigma}) \tag{3}$$

$$\Phi[\,\Sigma\,] \rightarrow \Phi'[\,\Sigma\,] = \exp\left[\, \frac{i}{2} \int_{\Sigma=\partial\Omega} dX^\mu \wedge dX^\nu\, \Lambda_{\mu\nu}(X) \,\right]\, \Phi[\Sigma]\ . \tag{4}$$

This extended $U(1)$ gauge symmetry, if spontaneously broken, has the same effect as the *global* $U(1)_{\rm PQ}$-symmetry as far as the generation of Nambu-Goldstone bosons is concerned. However, one difference is that because of eq.(3), such Goldstone bosons will be realized in the Kalb-Ramond representation of massless spin-0 fields [6]. A second and more important difference is that such bosons can be gauged away leaving only massive pseudoscalar particles in the physical spectrum. This is the essence of DHM.

The effect of the above properties on the inflationary-axion scenario is apparent in both the classical and quantum approach to Bubble Dynamics:

i) *Classical formulation.* The action functional of Bubble Dynamics can be defined in any number of dimensions as a generalization of the Einstein-Maxwell action for the dynamics of point charges on a Riemann manifold [7] . In four dimensions and under the assumption of spherical symmetry, the field equations of bubble dynamics are integrable [4] : the net physical result of the $A_{\mu\nu\rho}$-*bubble coupling* is the nucleation of a bubble whose boundary separates two vacuum phases of De Sitter type characterized by two effective and distinct cosmological constants, one inside and one outside the bubble. The evolution of the bubble, which is controlled by the two cosmological constants and by the surface tension, can be simulated by the one-dimensional motion of a fictitious particle in a potential; furthermore, a well defined algorithm exists [3,8] which is capable of determining all possible types of solutions, including inflationary ones, together with the region in parameter space where simple families of solutions can exist.

ii) *Quantum mechanical formulation.* The cosmological field represents the ultimate source of energy in the bubble universe. But how does matter manage to " bootstrap " itself into existence out of that source of latent energy? One possible scenario is as follows: as the volume of the bubble increases exponentially during the inflationary phase, so does the total (volume)energy of the De Sitter vacuum. At least classically. Quantum mechanically there is a competitive effect which is best understood in terms of an analogous effect in (1+1)-dimensions. In two dimensions a bubble is simply a particle-anti particle pair, moving " left " and " right " respectively, and the volume within the bubble is the linear distance between them. As the distance increases, so does the potential energy between them. Quantum mechanically, however, it is energetically more favorable to polarize the vacuum through the process of pair creation [9] , which we interpret as the nucleation of secondary bubbles out of the vacuum enclosed by the original bubble. The net physical result of this mechanism is the production of massive spin-0 particles [10] . The same mechanism can be lifted to (3+1)-dimensions and reinterpreted in the cosmological context: the $A_{\mu\nu\rho}$ field shares the same properties of the gauge potential A_μ in two dimensions and polarizes the vacuum via the formation of secondary bubbles [11] .

Consider now a spherical bubble and focus on the radial evolution alone. The intersection of any diameter with the bubble surface evolves precisely as a particle-anti particle pair in (1+1)-dimensions. However, since there is no preferred direction, the mechanism operates on concentric *shells* inside the original bubble. Remarkably, the final result is again the production of massive pseudoscalar particles in the bubble universe. However, while in two dimensions Goldstone bosons do not exist, in (3+1)-dimensions they do exist and have a direct bearing on the axion mass problem.

A second possible scenario, which best illustrates how DHM works, is the " Membrane Abelian Higgs Model ", recently proposed by the authors [12] . For imaginary surface tension the absolute value of the membrane field can acquire a non vanishing (constant)

vacuum expectation value and the extended gauge symmetry (3-4) is spontaneously broken; Goldstone bosons appear as Kalb-Ramond fields $\Theta_{\mu\nu}$. By rotating the original field variables to the unitary gauge, such Goldstone bosons are gauged away and one is left with a residual lagrangian which leads precisely to the field equations (1).

While the mathematical details are far from trivial [12] , the formal steps outlined above are familiar from the usual Higgs mechanism. The *dual* Higgs mechanism, however, differs in one crucial aspect. While in the usual Higgs mechanism the spin content of the gauge field is the same before and after the appearance of mass, a new effect occurs when the gauge field is $A_{\mu\nu\rho}$: when massless, $A_{\mu\nu\rho}$ is pure gauge, while equation (1) describes a massive particle with a definite value of spin (zero) in a representation which is dual to the familiar Proca representation of massive, spin-1 particles: the scalar component $\partial^\mu A^*_\mu$ of the pseudovector field A^*_μ is allowed to propagate as a free field by absorbing the Goldstone bosons.

It is a twist of Quantum Bubble Dynamics that the physical spectrum consists of massive pseudo-scalar particles and one might be tempted to identify them with the physical axions that might be present in our galactic halo. However, the difference in DHM is plain: axions are massless spin-0 Goldstone bosons represented by Kalb-Ramond fields while the physical spectrum consists of massive spin-0 particles represented by the $A_{\mu\nu\rho}$ -field.

Born out of the darkness of the cosmic vacuum, axions were invisible to begin with and remain invisible to the extent that they are " eaten up " by the cosmological field. According to DHM, what experimenters are searching for in the halo of our galaxy is the end product of a transmutation process which converts the self energy of the cosmological field into massive particles.

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